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Annotated Bibliography: Empirical and Analytical Methods for Geomechanical Modeling of Underground Structural Excavations, Stochastic Inversions Techniques, and Recent Developments in Interferometric Synthetic Aperture Radar (InSAR)

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Annotated Bibliography

Empirical and Analytical Methods for Geomechanical Modeling of Underground Structural Excavations, Stochastic Inversions Techniques, and Recent Developments in Interferometric Synthetic Aperture Radar (InSAR)

Geomechanical Modeling of Deformation Caused by Tunneling

Empirical Models

*Atkinson, J. H., and D. M. Potts, 1977. Subsidence above shallow circular tunnels in soft ground, J. Geotech. Eng. Div. ASCE, **103**, 307-325.*
One of the most useful aspects of this paper is that the authors provide a method of estimating the ***i*** parameter used in the most widely employed empirical method for predicting ground surface subsidence (vertical displacement) [Peck, 1969] (see below). The ***i*** parameter is estimated from information obtained from field observations and model tests. However, use of ***i*** values estimated using this method is restricted to similar tunneling situations as those dealt with in the paper.

Clough, G. W., and B. Schmidt, 1981. Design and performance of excavations and tunnels in soft clay, in: E. W. Brand and R. P. Brenner (Eds.), Soft Clay Engineering, Amsterdam: Elsevier, 569-634.
The authors present a method of estimating the ***i*** parameter used in Pecks's [1969] method, based on information obtained from field measurements above tunnels in the UK. Surface settlement predictions using this estimate of ***i*** would only be applicable to similar classes of tunneling and geologies as those described in the paper.

*Fang, Y. S., J. S. Lin, and C. S. Su, 1994. An estimation of ground settlement due to shield tunnelling by the Peck—Fujita method, Can. Geotech. J., **31**, 431-443.*
The authors present an empirical method to estimate surface subsidence above tunnels excavated using shield tunneling methods. The authors combine published measurements of the maximum surface settlement (S_{max}) from dozens of tunnels in Japan with the Gaussian subsidence (vertical displacement) profile template proposed by Peck [1969] to predict maximum and minimum surface subsidence profiles. Deformation data from single and multiple tunnels, from a variety of medium types, and a variety of construction techniques are employed. This method has the potential of being applicable to a variety of situations for which the stability ratio of the medium (which depends on the total overburden load, air pressure above atmospheric within the tunnel, and the undrained shear strength) is known or can be estimated.

*Lee, K. M., R. K. Rowe, and K. Y. Lo, 1992. Subsidence owing to tunnelling. I. Estimating the gap parameter, Can. Geotech. J., **29**, 929-940.*
The authors present a simple method to estimate the "gap" parameter, which is designed to quantify the major factors that contribute to the short-term ground deformation caused by constructing lined tunnels using tunnel boring machines. The gap parameter is a

function of the physical gap between the shield of the tunneling machine and the outer diameter of the lining, the 3D elasto-plastic deformation at the tunnel face, and the quality of the construction workmanship. This parameter can subsequently be input into both analytical and numerical models. Settlement estimates using the gap parameter require knowledge of certain construction specifics, which are not always available.

Mair, R. J., M. J. Gunn, and M. P. O'Reilly, 1981. Ground movements around shallow tunnels in soft clay, Proc. 10th Int. Conf. Soil Mech. Found. Eng., 323-328.
Using information obtained from field observations and centrifuge tests, the authors provide a method for estimating the $\boldsymbol{i}$ parameter used in the Peck [1969] empirical method. As with other methods, these estimates of $\boldsymbol{i}$ would only be applicable to similar classes of tunneling situations as those described in the paper.

*Mair, R. J., R. N. Taylor, and A. Bracegirdle, 1993. Subsurface settlement profiles above tunnels in clays, Géotechnique, **43**, 315-320.*
This paper describes an empirical method to determine subsurface subsidence above tunnels in clay based on Peck [1969]. Field data from three tunnels and measurements from centrifuge model tests are used to calibrate the empirical expressions.

Mair, R. J., R. N. Taylor, and J. B. Burland, 1996. Prediction of ground movements and assessment of risk of building damage due to bored tunnelling, Proc. Geotech. Aspects Underg. Constr. Soft Grnd., 713-718.
A method of predicting $\boldsymbol{S_{max}}$ for input into Peck's [1969] Gaussian relationship. The authors combine a previously published empirical determination of $\boldsymbol{i}$ (O'Reilly and New [1982] – see below) with an analytical relation for volume loss assuming a circular cross-section.

New, B. M., and M. P. O'Reilly, 1991. Tunneling induced ground movements: Predicting their magnitude and effect, Proc. 4th Int. Conf. Ground Move. Struct., 671-697.
The authors present estimates of the $\boldsymbol{S_{max}}$ and $\boldsymbol{i}$ parameters for input into a modified form of Peck's [1969] empirical method to calculate both vertical and horizontal displacements at the surface above single and twin tunnels. The authors suggest that this estimate of $\boldsymbol{S_{max}}$ would be best suited to tunnels in cohesive geomaterials like clays.

O'Reilly, M. P., and B. M. New, 1982. Settlements above tunnels in the United Kingdom—their magnitude and prediction, Proc. Tunneling '82, 173-188.
This paper presents a method of estimating the $\boldsymbol{i}$ and $\boldsymbol{S_{max}}$ parameters used in Peck [1969] for both cohesive and granular soils. The method is based on field observations above tunnels excavated within a variety of geomaterials in the UK. Thee authors also extend Peck's method to include an empirical relationship for horizontal displacements. The parameters estimated using this method are applicable only to similar tunneling situations and materials as those used to develop he method.

Peck, R. B., 1969. Deep excavations and tunnelling in soft ground, Proc. 7th Int. Conf. Soil Mech. Found. Eng., 225-290.
The empirical relationship presented in this seminal paper has become the most frequently adopted method to determine surface settlements above tunnels, particularly in soil. Peck observes that measured vertical displacement of the ground surface above a tunnel along profiles perpendicular to the tunnel axis can be predicted using a Gaussian

curve that depends only on the maximum surface settlement above the tunnel centerline, S_{max}, and the point of inflection of the settlement curve, ***i***. Subsequently, numerous authors have published a variety of methods for estimating values of S_{max} and ***i*** for different classes of tunneling scenarios. It has been shown that this method provides less than satisfactory results in granular media [New and O'Reilly, 1991] and overconsolidated clays [Eisenstien et al., 1991].

Analytic Models

*Chi, S.-Y., J.-C. Chern, and C.-C. Lin, 2001. Optimized back-analysis for tunneling-induced ground movement using equivalent ground loss model, Tunn. Underg. Space Tech., **16**, 159-165.*

The authors present an extension of the "equivalent ground loss" model of Loganathan and Poulos [1998] (see below) to enable it to be applied to both clays and sands. The tunnels used in the calibration procedure were constructed as part of the Taipei Rapid Transit System, and had depths as great as 22 m. The authors present simple analytical expressions for vertical and horizontal surface and subsurface displacements. The "gap" parameter and a method to account for the effect of grouting are also included in the solution.

*Einstein, H. H., and C. W. Schwartz, 1979. Simplified analysis for tunnel supports, J. Geotech. Eng. Div. ASCE, **105**, 499-518.*

This paper describes the derivation of a 2D plane strain analytical solution for calculating displacements and stresses in an infinite elastic Earth and the tunnel liner using a relative stiffness method. Their simplifying assumptions ignore the effects of the free surface, implying that the in-situ stresses are small compared to the strength of the medium (i.e. that failure is not imminent), and assume a hydrostatic stress state. These assumptions limit application of the solution to deep tunnels in rock under hydrostatic stress. Surface displacements cannot be calculated.

*Gonzales, C., and C. Sagesta, 2001. Patterns of soil deformation around tunnels. Application to the extension of the Madrid Metro, Computers and Geotechnics, **28**, 445-468.*

Gonzales and Sagesta present a good summary of the state-of-the art in 2D analytical modeling of deformation induced by tunneling through 1999. They consider elasto-plasticity but not tunnel buoyancy. They tested models against ground deformation observations from 57 well-instrumented sections of an extensions to the Madrid Metro and conclude that deformation patters can be simulated with reasonable accuracy over a large range of cases.

*González-Nicieza, C., A. E. Álvarez-Vigil, A. Menéndez-Díaz, C. González-Palacio, 2008. Influence of the depth and shape of a tunnel in the application of the convergence-confinement method, Tunn. Underg. Space Tech., **23**, 25-37.*

The convergence-confinement method is a commonly used for tunnel support analysis and design in rock. González-Nicieza et al. present a modification to this axisymmetric method that would account for the effect of depth and tunnel cross-sectional shape (both axisymmetric and non-axisymmetric) when predicting the radial convergence of a lined tunnel. This estimate would then provide the input into another analytical or numerical model to predict surface displacements.

Klar, A., 2006. the effect of tunnel buoyancy on ground settlement in elastic soil, *Electronic J. Geotech. Eng., Paper 2006-0695, www.ejge.com/2006/Ppr0695/Ppr0695.htm, 7 p.*
Klar points out that some analytical solutions that use tunnel displacement boundary conditions ("ground loss") to predict surface deformation (e.g. Verruijt & Booker, 1996; Verruijt, 1997) neglect the buoyancy effect that results from the excavation of material. He then goes on to demonstrate the significance of the buoyancy effect by comparing results obtained using Verruijt's (1997) analytical solution with results from the commercial FLAC2D finite difference code. One important point that emerges from these demonstrations is that the magnitudes of displacements calculated in a homogeneous elastic half-plane under plane strain using finite difference and finite element methods (as well as 2D exact solutions) are inherently arbitrary to some degree, and depend on the depth at which the rock is chosen to be rigid, i.e. where the zero-displacement lower boundary of the model is placed. (This problem does not occur when there is an increase of rigidity with depth.)

*Li, S.-C., and M.-B. Wang, 2008a. An elastic stress-displacement solution for a lined tunnel at great depth, Int. J. Rock Mech. Mining Sci., **45**, 486-494.*
This paper describes the development of 2D plane strain analytical expressions for stress and displacement within a tunnel liner and the surrounding material, using the complex potentials method of Muskhelishvili [1953]. The solutions are for pressurized circular tunnels with elastic liners in an infinite, homogeneous linear elastic medium under homogeneous in-situ pre-stress. The infinite medium assumption means that these solutions are of limited use in estimating displacements at the ground surface.

*Li, S.-C., and M.-B. Wang, 2008b. Elastic analysis of stress-displacement field for a lined circular tunnel at great depth due to ground loads and internal pressure, Tunn. Underg. Space Tech., **23**, 609-617.*
This paper follows the same approach as Li and Wang [2008a] for different stress boundary conditions.

*Loganathan, N., and H. G. Poulos, 1998. Analytical prediction for tunneling-induced ground movements in clays, J. Geotech. Geoenv. Eng., **124**, 846-856.*
This paper describes a semi-analytical model that combines empirical estimates of the "gap" parameter [Lee et al., 1992] with the analytical solution of Verruijt and Booker [1996] to better determine deformations due to tunneling in clays. The authors show that this "equivalent ground loss" model predicts surface settlement troughs in clays that more closely resemble observations than the Verruijt and Booker [1996] solution. However, the computed deformation troughs are still wider than actual observations and estimates derived from purely empirical methods. The addition of empirical components to the analytical solution inevitably reduces its generality. Therefore, it is not clear to what extent this model is applicable to tunneling in other geomaterials an in other situations.

Muskhelishvili, N.I., 1953. Some Basic Problems of the Mathematical Theory of Elasticity, Noordhoff, Groningen, The Netherlands, 704 p.
This classic text lays develops the fundamental mathematical framework for solving problems of two-dimensional elasticity using the complex variable approach.

*Pender, M. J., 1980. Elastic solutions for a deep circular tunnel, Géotechnique, **30**, 216-222.*
Pender developed simple closed-form solutions for displacements and stresses induced by a circular tunnel in an infinite, homogeneous, linear elastic plane under different stress loading conditions. The case of a pre-stressed medium is appropriate to real tunneling situations under gravity loading. The infinite-medium solutions are appropriate for calculating displacements and stresses induced by deep tunnels, where the effect of the free surface on the deformation of the tunnel negligible. These solutions cannot be used to calculate displacements at the free surface, but can be used to calculate the displacements of the walls of a deep tunnel, which can then be used as displacement boundary conditions in a dislocation-type half-space solution such as Verruijt and Booker [1996].

*Sagesta, C., 1987. Analysis of undrained soil deformation due to ground loss, Geotechnique, **37**, 301-320.*
Sagesta developed closed-form approximate 2D and 3D solutions for deformations resulting from excavation of a circular tunnel in an isotropic, homogeneous, incompressible (i.e. Poisson ratio equal to 0.5) half-space. His approach utilized an image technique similar to that employed by Verruijt and Booker [1996], summarized below, and his incompressible solutions are limiting cases of their more general elastic theory.

Strack, O.E., 2002. Analytical solutions of elastic tunneling problems, Ph. D. thesis, Technische Universiteit Delft, The Netherlands, 103 p.
Strack's thesis covers in detail the recent development of complex variable solutions to 2D elastic plane strain tunneling problems that are the subject of papers by Verruijt, Booker, Strack and others cited here (Strack was the student of Prof. A. Verruijt).

*Strack, O. E., and A. Verruijt, 2002. A complex variable solution for a deforming buoyant tunnel in a heavy elastic half-plane, Int. J. Numer. Anal. Meth. Geomech., **26**, 1235-1252.*
This is a further development of the exact analytical solutions of Verruijt [1997] that incorporates the effect of tunnel buoyancy for the class of problems having prescribed displacements at the tunnel boundary. Buoyancy results in a rigid body upward displacement of the tunnel as a whole (see the annotation for Verruijt & Booker [2000], below).

*Verruijt, A., 1997. A complex variable solution for a deforming circular tunnel in an elastic half-plane, Int. J. Num. Anal. Meth. Geomech., **21**, 77-89.*
This paper develops an exact 2D plane strain solution for deformations due to a circular tunnel in an isotropic, homogeneous, linear elastic half-plane using the complex potential method of Muskhelishvili [1953] and a conformal mapping on to a unit annulus. The solution is in the form of an infinite Laurent series expansion of the stress function, the coefficients of which must be determined recursively by a combination of analytical and numerical computations. The boundary conditions at the tunnel are prescribed displacements of the tunnel wall. Gravity is not considered. One result of applying the solution is that, in the absence of buoyancy, the tunnel as a whole is required to undergo a downward rigid body translation.

Verruijt, A., 1998. Deformations of a circular half-plane with a circular cavity, Int. J. Solids Structures., 35, 2795-2804.
The same approach as in Verruijt [1997] applied to the problem of a circular tunnel in a gravity-free homogeneous, linear elastic half-plane with prescribed stresses at the tunnel boundary.

*Verruijt, A., and J.R. Booker, 1996, Surface settlements due to deformation of a tunnel in an elastic half plane. Geotechnique, **46**, 753-756.*
Verruijt and Booker derive an approximate 2D plane strain solution for deformations resulting from a circular tunnel in an homogeneous linear elastic half-plane. The derivation uses the singular solution for a point center of convergence in an infinite plane. The displacement and stress boundary conditions on the free surface are satisfied by introducing an image point source symmetrically on the opposite side of the surface boundary, and a Boussinesq distribution of point forces on the boundary. The solution is approximate in that it does not take into account the effect of the imposed surface forces on the deformation of the tunnel wall. This effect has been shown to be negligible for source depths greater than two tunnel radii. The deformation solution is driven by prescribing displacements of the tunnel wall relative to the original tunnel radius. The prescribed displacements include both uniform radial convergence and tunnel "ovalization". However, Strack [2002] pointed out that the ovalization terms in the solution are incorrect.

Verruijt, A., and J.R. Booker, 2000. Complex variable analysis of Mindlin's tunnel problem, in: Smith and Carter (eds.), Developments in Theoretical Geomechanics, Balkema, Rotterdam, 1-20.
In a further development of the complex variable approach of Verruijt [1997] to solving plane strain problems related to a tunnels in an elastic half-plane, this paper addresses the stress and displacement fields resulting from deformation of a circular tunnel introduced into a medium under gravitational stresses. Whereas Mindlin [1940, *Trans. ASCE, 1117-1153*] derived the solution for the stress perturbations, Verruijt and Booker derive solutions for both stresses and displacements throughout the half-plane and on the free surface. The solutions are not given explicitly, but in the form of complex potentials series from which the stresses and displacements can be derived after the coefficients have been recursively determined. Rather than prescribed displacements of the tunnel wall, the boundary conditions are the in-situ stresses under gravitational loading, under which the tunnel is free to deform. These boundary conditions result in a buoyancy component in the displacement solution, which displaces the entire tunnel upwards and produces surface heave that offsets the subsidence. However, solutions like this that involve a non-zero resultant force – in this case the buoyancy force corresponding to removal of the material within the tunnel - in an homogeneous half-plane have, in general, a logarithmic singularity that results in unbounded displacements at infinity (Muskhelishvili, 1953, p.128). This means that the displacement field is determined only to within a rigid body displacement . For practical purposes, a point far from the tunnel is deemed to be fixed by adding a constant vertical displacement to the solution.

*Verruijt, A., and O.E. Strack, 2008. Buoyancy of tunnels in soft soils, Geotechnique, **58**, 513-515.*
This summary paper is a concise consolidation of the recent work by Verruijt and Strack on the effect of buoyancy effects, and specifically the effect on surface displacements over tunnels in soft soils under gravity loading. The conclusion is that the buoyancy

effect can be large enough to explain the shallower and narrower subsidence troughs usually observed over tunnels in soft soils compared with those predicted by elastic models that ignore buoyancy.

Wang, M.-B., and S.-C. Li, 2008. A complex variable solution for stress and displacement field around a lined circular tunnel at great depth, Int. J. Numer. Anal. Meth. Geomech, www.interscience.wiley.com, DOI: 10.1002/nag.749.
The authors present a minor extension of the work by Li and Wang [2008a,b] for tunnel deformations in an infinite medium. They modify the original analytical solutions and present solutions for stresses and displacements associated with two special cases.

Stochastic Inversion

Tarantola, A., 2005. Cascaded Metropolis algorithm, Inverse Problem Theory, Chap. 6 – Appendices – Sec. 6.11, SIAM, Philadelphia, PA.
The cascaded Metropolis algorithm (CMA) may be useful in reducing the computational expense of our inversion approach. CMA would allow combination of InSAR (range change) data collected at different resolutions in the joint inversion. The general idea is that for each subsurface facility model we need to predict the range change that would be observed if the model is a "true" representation of the configuration of the subsurface facility. Predicting the range change at a lower resolution will be less computationally intensive than at higher resolution. The CMA would allow us first to test a proposed trial model at a low resolution. If the proposal is rejected, a new proposal is generated and tested against the lowest resolution data. If the proposal is accepted, the proposal is checked against InSAR data collected at the next resolution level, and so on until the proposal is tested against the highest resolution data. This approach would reduce the computational burden because models that are inconsistent with the lower resolution data are quickly rejected. The most expensive computations are performed only on models that are more likely to be accepted when tested against the highest resolution data.

Rabiner, L.R, 1989. A tutorial on hidden Markov models and selected applications in speech recognition, Proc. IEEE, 77, 257–286.
A hidden Markov model (HMM) is a statistical model in which the system being modeled is assumed to be a Markov process with unknown parameters. The challenge is to determine the hidden parameters from the observations. Our particular goal is to determine the unknown configuration of openings that make up a subsurface facility, for which treating this problem as an HMM may have some promise. For example, suppose that we know that a subsurface facility has one portal and a ventilation shaft. Furthermore, suppose that, based on construction practice, one can determine that: (1) possible types of openings are high bays, tunnels, workrooms, ramps and shafts; and (2) the transition probabilities between these types of openings can be estimated; e.g. the probabilities that a ventilation shaft is connected to a high bay or to a work room are 0.6 and 0.1, respectively. An HMM can be envisioned that predicts the likely configurations of a facility. For example, one likely configuration may be a portal connected to a tunnel that is in turn connected to a high bay..., and so on. A less probable configuration may be a portal connected to a tunnel that connects to a workroom.… This approach would use prior information pertaining to the subsurface facility and produce proposed facility models that are consistent with that information.

*Forney, G.D., 1973. The Viterbi algorithm, Proc. IEEE, **61**, 268–278.*
The Viterbi algorithm is designed to find the most likely sequence of hidden states that results in a sequence of observed events, in the context of HMM. This paper describes the algorithm in detail. The Viturbi algorithm would be adapted to the HMM approach described above if we choose to implement that approach.

Advanced InSAR Processing

*Berardino, P., G. Fornaro, R. Lanari, and E. Sansosti, 2002. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms, IEEE Trans. Geosci. Remote Sens., **40**, 2375-2383.*
Small BAseline Subset (SBAS) is an advanced stacking technique that minimizes the spatial and temporal decorrelation that are among the main limitations of both conventional InSAR and Persistent (or permanent) Scatterer InSAR (PSInSAR). Like PSInSAR, SBAS processing also improves signal-to-noise ratio (SNR) by reducing topographic and atmospheric artifacts. Available scenes from different satellite orbits are first organized into sub-groups, each containing interferometric pairs having small temporal and spatial baselines to minimize decorrelation. Interferograms are formed from each pair and phase unwrapped individually. The groups are then linked to construct a continuous displacement time series for each pixel employing a singular value decomposition (SVD) inversion for displacement rate. Atmospheric artifacts and errors in the digital elevation model (used to remove the topographic phase component) are identified based on their temporal and spatial correlation characteristics, and are then removed by cascade bandpass filtering. The advantage of SBAS is that while improving SNR it preserves the dense spatial sampling characterizing conventional InSAR, rather than retaining only a subset of pixels as is done in PSInSAR. However, forming the individual interferograms typically includes multi-looking (spatial smoothing) to improve phase coherence, so that the benefit of the full resolution inherent in the data is lost. In addition, temporal decorrelation remains a limitation in vegetated and cultivated areas, etc., particularly for X- and C-band radar data.

*Eineder, M., N. Adam, R. Bamler, N. Yague-Marinez, and H. Breit, 2009. Spaceborne spotlight SAR interferometry with TerraSAR-X, IEEE Trans. Geosci. Remote Sens., **47**, 1524-1535.*
One meter-resolution SAR data has recently become available from the TerraSAR-X and COSMO-Skymed (X-band) satellites operated in spotlight mode. Einder et al. explain the differences between interferometric processing of data acquired in spotlight mode and conventional strip-map mode, outline the key processing steps, and evaluate the critical parameters, particularly the time-variable Doppler frequency over an acquisition caused by steering the radar beam to keep the target area illuminated (i.e. change in squint angle) and acquisition start time. The authors convincingly demonstrate that very high resolution differential interferograms can be obtained from X-band spotlight mode data by showing rather spectacular singe-pair interferograms for two urban settings. The key attributes are the 1 m resolution and the higher radar frequency, which mean that a scene is populated by many more phase-stable scatterers than at C band. X-band decorrelates more rapidly than C band, but this is compensated to some extent by the shorter revisit times of the X-band satellites (11 days for TerraSAR-X and 2 days for the COSMO-

Skymed constellation - compared with the 24 and 35 days revisit of the RADARSAT-2 and ENVISAT C-band satellites, respectively).

*Ferretti, A., G. Savio, R. Barzaghi, A. Borghi, S. Musazzi, F. Novali, C. Prati, and F. Rocca, 2007. Submillimeter accuracy of InSAR time series: Experimental validation, IEEE Trans. Geosci. Remote Sens., **45**, 1142-1153.*
In this paper the originators of the Permanent (persistent) Scatterer InSAR (PSInSAR) method verify experimentally the accuracy that it can achieve under ideal conditions. The blind experiment consisted of two pairs of corner reflectors, each having one fixed reference and the other adjustable to within 0.3 mm in the vertical and EW directions. Both reflector pairs were imaged during 55 (25 ascending, 30 descending) RADARSAT-1 orbits and 28 (10 ascending, 18 descending) ENVISAT orbits, each of the adjustable reflectors being moved a few mm between successive orbits. Line-of-sight range change displacement time series were measured for each of the reflectors using PSInSAR processing. Combining the data from ascending and descending orbits allowed the vertical and horizontal displacements to be resolved from the range changes (the first time this has been demonstrated in practice). The standard deviations of the error were 0.75 mm and 0.58 mm in the vertical and EW directions, respectively. This experiment is a convincing demonstration that PSInSAR can measure displacements of ideal permanent scatters with sub-mm accuracy.

*Hooper, A., 2008. A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches, Geophys. Res. Lett., **35**, L16302, doi:10.1029/2008GL034654, 5 p.*
Hooper describes a method that combines his approach to persistent scatterer InSAR (StaMPS) with the small baseline approach (SBAS; see Berardino et al., 2002, above) to maximize spatial resolution and reduce phase unwrapping errors. Persistent scatter (PS) InSAR is optimized for a scattering model in which a single strong scatterer dominates the radar return from a particular pixel (a PS), whereas SBAS is optimized for a multi-scatterer model. The two approaches are complementary in that every radar scene comprises a mix of both pixel types. In effect, the hybrid method selects two overlapping sets of pixels from two sets of scene pairs formed from the available SAR coverage. The first are persistent scatterers selected according to the StaMPS algorithm from pairs formed against a single master orbit. The second are multi-scatterer pixels that decorrelate only slowly (termed slowly-decorrelating filtered phase, SDPF, pixels), selected using the StaMPS algorithm from short baseline pairs (multiple master orbits) after spectral filtering. The PS and SDPF – which are much more numerous – are combined at the phase unwrapping stage. Processing is carried out at full resolution, which, unlike SBAS, allows the dense spatial sampling inherent in the data to be retained.

*Lanari, R., F. Casu, M. Manzo, G. Zeni, P. Berardino, M. Manunta, and A. Pepe, 2007. An overview of the Small BAseline Subset algorithm: A DInSAR technique for surface deformation analysis, Pure. App. Geophys., **164**, 637-661.*
This is a review of the theory and applications of the SBAS algorithm developed by Berardino et al.. [2002] (see above). Evaluation of application of the technique to three different deformation scenarios indicate that it is typically capable of imaging ground surface displacement time series and mean displacement rates on a broad areal scale with accuracies of ~5 mm and ~1 mm/yr, respectively. (See also *Casu et al., 2006, Rem. Sense. Envr., **102**, 195-210.)*

Lauknes, T.R., J. Dehls, Y. Larsen, K.A. Høgda, and D.J. Weydahl, 2005. A comparison of SBAS and PS ERS InSAR for subsidence monitoring in Oslo, Norway, *Proc. Fringe ATSR Wksp. 2005,* *Frascati, Italy, 28 Nov –2 Dec, 2005,* *http://earth.esa.int/fringe2005/proceedings*.

Lauknes et al. describe Small BAseline Subset (SBAS) processing to monitor subsidence under Oslo. Even though Nordic environments are not ideal for InSAR because of steep terrain and snow cover for substantial parts of each year, the authors were able to obtain clear displacement images within the city and nearby areas. In a cursory comparison, SBAS and persistent scatterer InSAR results show good agreement in the urban and suburban areas.